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MODELING WATER AND NITROGEN BEHAVIOR IN THE SOIL-PLANT SYSTEM

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SUMMARY

A set of dynamic mathematical relations is developed for the major variables of soil water, nitrate, ammonium, available organic nitrogen, and plant growth and nitrogen uptake. Daily climatic conditions are used to control evapotranspiration and modify the rates of plant growth and soil processes. Inputs of irrigation water and fertilizer can be controlled to reduce leaching of nitrate.

Introduction

Water and nitrogen are the two most limiting factors of crop growth that can be controlled, especially in the semiarid West where most of the water requirement during the growing season is furnished by irrigation. With increasing competition for water and concern for the nitrate pollution of our environment, agriculture must optimize the growth factors that can be controlled. Since irrigation water may leach nitrate out of the root zone, the system can not be optimized by considering the variables separately. In order to evaluate the numerous combinations of time and amount of both water and fertilizer applications, a mathematical model is essential.

A second objective of developing a model is to provide a research tool for assessing our understanding of the behavior of water and nitrogen in the soil-plant system. A good predictive model can be developed for a given crop and area with empirical relations, but for a universal model, the empirical relations must be replaced by sound scientific principles. The replacement of empirical relations provides the opportunity to evaluate our current understanding and to suggest new areas of research.

The Model

General

The main objective of the current model is to estimate the behavior of water and nitrogen in the root zone from crop emergence to harvest. Plant growth is very important in this model, but it is not modeled in detail because the objectives are centered in the soil. The detail is only sufficient to provide an expanding root zone, a sink for nitrogen and water, and a means of measuring the response to environmental conditions. The flow diagram of the model is given in Figure 1. The relations used are described in detail and are as general as possible so that they might be applied to a number of different crops and areas. The specific numerical values used to test the model are for sugarbeets grown on a Portneuf silt loam in Idaho.

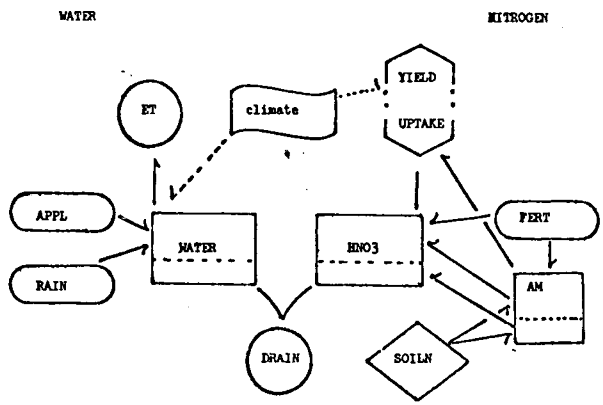

Figure 1. A flow diagram of the model: Water and nitrogen in the soil-plant system.

Water

Changes in soil moisture occur by evapotranspiration, rainfall retained on the crop-soil surface or entering the soil, irrigation water applied, and drainage from the soil profile. Daily evapotranspiration estimates are obtained using an equation to estimate potential evapotranspiration and a crop coefficient.

The modified Penman equation requires the daily meteorological data of minimum and maximum temperature, solar radiation, dew point temperature and the wind run at a known height[1]. The wind run is the windspeed integrated over the entire day. The crop coefficient represents the combined relative effects of the resistance of water movement from the soil to the various evaporating surfaces and the resistance to the diffusion of water vapor from the surfaces to the atmosphere, and the relative amount of radiant energy available as compared to the reference crop represented by the potential evapotranspiration. At present the coefficient is an empirical function of soil moisture that changes for each crop and each stage of growth for that crop. Once sugarbeets growing in the Portneuf soil achieve full crop cover, the stage of growth relation remains constant. The value of the crop coefficient, K_c, under these conditions is illustrated in Figure 2 as a function of available water. The

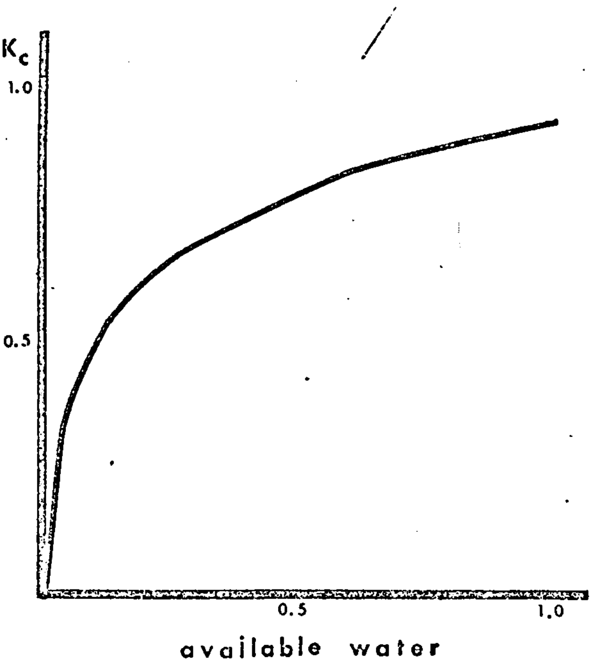

Figure 2. The crop coefficient of sugarbeets with a closed cover as a function of available water.

available water is the soil water content between field capacity and the wilting point. This part of the model has been developed and tested, and is being used to schedule irrigations[2,3,4].

The approximate equation for drainage when there is no withdrawal of water by plants, is

$$W = W_o t^{-m} \qquad (1)$$

where W = the water content in the profile at time t after drainage began, W_o = the water content when t = 1, and m is a constant derived experimentally for a given soil profile[5]. This technique basically assumes that the hydraulic gradient during drainage with evapotranspiration is the same as during drainage without evapotranspiration and the drainage rate varies primarily with the change in hydraulic conductivity as the water content decreases.

Laboratory studies indicate that this approach may be the most reliable and conservative approximation of drainage, providing several time increments are used for the first few days after irrigation, or the evapotranspiration for the day is subtracted first[6]. This approach does require determining the time-dependent drainage function for the soil profile in question. For example, the water content in the 0- to 60-cm depth of Portneuf silt loam based on the 1966 field tests is $W = 21.4t^{-0.043}$. From this equation, the derivative, dW/dt, can be calculated as a function of time, and then dW/dt as a function of W can be determined.

This equation is applicable after the irrigation or rainfall has penetrated the full depth of the root zone; therefore, a time lag must be considered before beginning to compute the rate of drainage.

Plant Growth

The increase in accumulated dry matter during the season follows an S-shaped curve. The integral of the normal curve is also an S-shaped curve, and therefore the rate of plant growth under ideal conditions during the growing season is assumed to follow the normal bell-shaped curve, Figure 3. The ideal rate of growth in kilograms of dry matter per hectare per day on

$$Y = Ym \ \exp\{-[M-X]^2/B^2\}$$

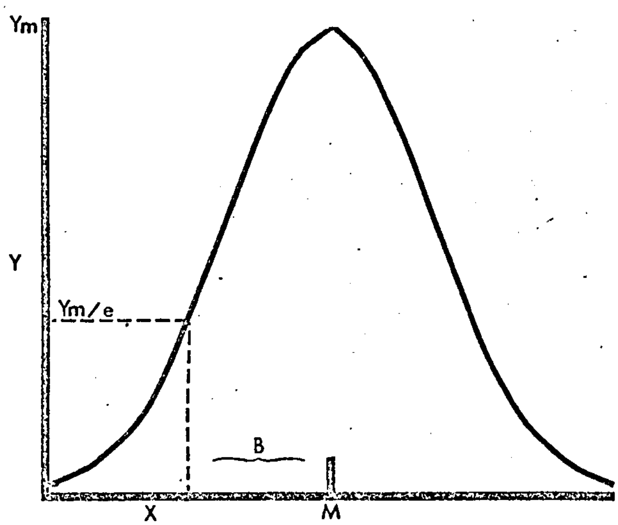

Figure 3. The normal or bell-shaped curve used for rates of growth and responses to environmental conditions.

day X after emergence is Y. Ym is the maximum rate obtained on day M, and B is half the width of the peak at 37% of the maximum. The growth of crops in the field seldom achieves the ideal rate because one of several growth factors may be limiting. Therefore, the parameters for the growth rate equation can only be determined after the effects of the limiting factor are corrected. It is expected that with the 3 or 4 years of field data available it will be possible to select good approximations for these parameters.

Plant physiology identifies the four most important growth factors as: water, temperature, light, and nitrogen. Agronomic experience shows that when one variable, such as temperature, is limiting then changes in the other variables, such as water, have minor effects. Therefore, Liebig's "Law of the Minimum" is used and the value of only the most limiting factor is considered to be operating.

The response of plant growth to increasing amounts of these factors is a curve with a maximum at the optimum amount. For water the best relation available is the ratio of the actual evapotranspiration to evapotranspiration that occurs when water is not limiting. This ratio is the crop coefficient, K_c, discussed in the section Water and illustrated in Figure 2. For the other three factors the normal curve is used as the response surface. It is recognized that the real response curve is not necessarily symetrical and in these cases the value of B can be changed as X exceeds the midpoint M. A temperature optimum of $24^{\circ}C$ and a B value of $16^{\circ}C$ is found in the literature[7]. An individual sugar beet leaf becomes light saturated at about 150 langleys (cal/cm^2) /day with 125 for the B value[8]. For field conditions we double the values to account for shading and neglect the response above light saturation.

Growth response to nitrogen appears to be more complex, although good quantitative data on the nitrogen requirements during the season are lacking. Experimental data indicate that for most crops the nitrogen content decreases during the season. The nitrate content of the sugarbeet petiole appears to be the most sensitive indicator of the nitrogen status of the plant. Unfortunately, this is of no help in modeling because the mechanisms of increase and decrease of this parameter are unknown. Since nitrogen is relatively mobile in the plant, we bridge these gaps for the present by considering the controlling variable to be total plant nitrogen as a percent of the dry matter. For lack of better information the optimum percent nitrogen is the percent nitrogen measured in plants grown on high fertility soils with a high moisture level. The nitrogen content presented in Figure 4 for sugarbeets grown in 1967 is used as the present estimate of the optimum N level. Plants appear to be more efficient in nitrogen use as it becomes limiting, thus the 37% level of effect is assumed to occur at 25% of the optimum nitrogen percent, giving a B value of 75%.

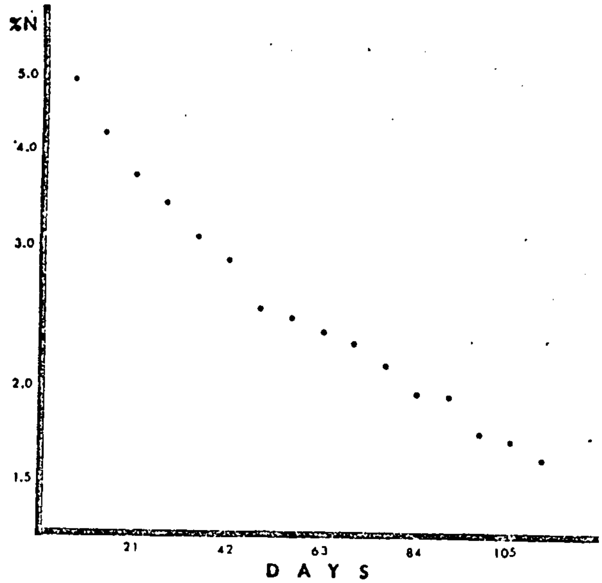

Figure 4. The percent nitrogen in the total dry matter of sugarbeets when measured on different days after emergence.

The rate at which the rooting depth increases is considered to ideally follow the equation of a normal curve, with a maximum rate of 3 cm/day at 80 days and a B value of 30 days. The ideal rate is reduced by the same factor that reduces growth. The experimental areas being used to develop the model have a hard pan at 46 cm, which prevents deeper root growth. This limitation is incorporated into the model.

Nitrogen

Nitrogen is considered to exist in three forms in the soil; nitrate, ammonium, and soil N. The pools of nitrate and ammonium are divided into two parts: the current root zone and the remaining potential root zone. This separation is necessary to account for root growth into new areas of different nitrogen composition.

The plant uptake rate of nitrate and ammonium from the current root zone is calculated as being proportional to the growth rate and related to the concentration of nitrate and ammonium in the root zone. The logic of the uptake rate being proportional to the growth rate derives from the fact that a slowly growing plant takes up considerably less nitrogen than a vigorously growing plant. The concentration (C) relation is the one usually found in nutrition studies[9]; Uptake = $A \cdot C / (D+C)$. The numerical estimates from some field data for the constants are A = 0.015, which includes the growth proportionality constant, and D = 10 kg N/ha. A large part of the ammonium is adsorbed on the soil, so the effective concentration for ammonium uptake is considered to be 10% of the total concentration.

Ammonium is converted to nitrate by way of nitrite. Under most conditions the nitrite concentration is never high, permitting the rate of conversion to be described as proportional to the ammonium concentration. The literature indicates that the proportionality constant can vary between 1.0 and 0.01. It was estimated to be 0.1 per day for this soil[10].

The variable, soil N, is used to denote the amount of organic N in the soil that can be converted to available nitrogen during the growing season. Studies of mineralization show that the rate of ammonium produced decreased with time (t) according to the relation[11]; Amount of Ammonium = $S\ t\ /(K+t)$. S is the maximum amount of ammonium that can be produced and in this model is considered to be the initial value of soil N. From the preceeding relation it is found that the rate of ammonium production is proportional to the square of the current soil N concentration. The proportionality constant is 1/SK. Preliminary experiments indicate S = 13 kg N/ha-cm and $1/SK = 11 \times 10^{-4}$ (kg N/ha/cm/day)$^{-1}$.

The rate constants for ammonification and nitrification are for ideal conditions. Soil moisture content and soil temperature are considered to be the two most important factors limiting these rates. For lack of better information the normal curve is again used as the response function. The optimum temperature is 30°C with 16° for a B value[12]. The optimum water content is 80% of the porosity and the B value is calculated from a 10% rate at the wilting point[13]. The values for this soil are 0.40 and 0.18. The most limiting value is selected as the modifying factor.

Management Practices

There are two different water--fertilizer management practices that must be considered. The first is rain, sprinkler irrigation, or flood irrigation with broadcast application of the fertilizer. In this case the nitrate and ammonium pools in the root zone are increased by the amount of applied fertilizer on the day of fertilization or after a short time lag. The toxic nature of high ammonium concentrations causes a delay in the ammonium conversion of 1 nitrate leached out of the actual root zone into the potential root zone and then out of the potential root zone is calculated as the product of water moved and nitrate concentration.

The other management practice is furrow irrigation with the fertilizer banded between the furrow and the plants. Assuming reasonable accuracy in placement and irrigation, the simplest approach is to consider that the first irrigation after fertilization does not leach any of the fertilizer nitrate out but causes it to be uniformly distributed in the entire root zone after drainage has stopped. Subsequent irrigations will behave as in the case of broadcast fertilizer application. It is possible, and may be necessary, to model this irrigation--placement interaction in much more detail to account for poor placement and/or excessive irrigations.

Use of the Model

The model has been programed in FORTRAN so that the behavior of the system can be simulated by a digital computer. Model parameters that have not been evaluated independently will be adjusted so that the model can simulate the behavior measured in field experiments. Using the same internal parameters with different initial conditions and climate, the model will be tested against data from field experiments of other years. The model will be considered acceptable as a first approximation when the results from the model simulation compare favorably with the experimental data. Some 21 parameters and initial conditions have been selected for a sensitivity analysis of the effect of systematic variation on the model behavior. The results of this study should indicate parameters and relations that need additional refinement.

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